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5. MISSION STUDIES

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INTRODUCTION

The preceding papers have discussed in some detail the elements that go into the design of an aircraft sytem and have indicated the most promising choices for each component. It is the purpose of this paper to blend all of these elements into predictions of the performance capabilities of complete aircraft systems. The aircraft systems investigated are required to perform a particular mission - long-range supersonic bombardment. Generally speaking, there are two ways of accomplishing such a mission. The first, and most conventional, is to have a manned bomber aircraft fly out to the target, deliver its payload, and fly back to its base. The second is to send a guided missile on a one-way flight to the target. Both of these methods have been considered.

The two methods of bomb delivery required the examination of aircraft performance for the two zones indicated in figure 1, where altitude is plotted against cruise Mach number. The class of turbine engines has been considered only for the propulsion of manned aircraft. The zone of application considered for such airplanes ranges over Mach numbers from 3 to 4.5 and altitudes from 60,000 to 110,000 feet. The ramjet engine has been considered only for the propulsion of missiles. These missiles were studied over a range of Mach numbers from Mach 5 to 9 and altitudes from 80,000 and 130,000 feet.

To determine the performance potential of these bombardment systems, series of airplanes and missiles were designed for their respective zones of application and the radius or range obtainable was computed. In any such analysis the results are highly dependent on the assumptions made. Some of the major assumptions will be discussed herein. In presenting the results, the effects of such variables as flight speed, target altitude, fuel type, and system and payload weights will be examined. It is neither the purpose nor intention of this paper to argue the merits of any one system of payload delivery over another. Rather, it is desired to present, in a factual manner, the performance capabilities the analyses have indicated for the systems studied.

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MANNED AIRPLANES

Engines

Of the gas-generator type powerplants discussed in paper 3, two of the more promising types have been chosen for discussion of flight capabilities in terms of absolute radius. These are a single-spool turbojet and an air-turborocket with air liquefaction. Although some of the more complicated engines such as the fuel-rich ducted fan and the hydrogen expansion cycle indicated radii of the same magnitude, the turbojet was chosen because, being a relatively familiar and simple engine, it would require less time to develop and also it can accommodate various types of fuels. The air-turborocket was chosen as a representative of the more complicated engines that indicated a relative range somewhat greater than the turbojet. 4793-I

Some of the pertinent design parameters of representative engines that appear to hold promise of good flight capabilities at Mach numbers between 3.0 and 4.5 are listed in table I. For the Mach 3.0 engine, designed for an altitude of about 65,000 feet, a sea-level compressor pressue ratio of 5.0 was used. At the higher design flight Mach numbers and altitudes where the engines operate more like ramjets, a sea-level pressure ratio of 2.3 was selected. Turbine-inlet temperatures of 1900° and 2500° R were chosen. The 2500° R temperature assumes either turbine cooling or coated molybdenum turbine blades. This higher turbine-inlet temperature indicates improvements in aircraft radius, but the engine would be somewhat more complicated. For all engines considered, the afterburner temperature during takeoff and acceleration is 4000° R. The air-turborocket cycle with air liquefaction uses hydrogen as fuel. It has a sea-level pressure ratio of 1.71 and a turbine-inlet temperature of 2000° R.

In general, the mission capabilities to be discussed will employ engines that have inlets and outlets with some variation in geometry. A variable inlet was chosen to reduce additive drag during the transonic flight conditions below that of a fixed inlet but far from that of an ideal inlet with no additive drag. The ejector-type exhaust nozzle has a variable throat and a fixed divergent section. Penalties in nozzle efficiency were imposed at flight conditions other than design.

Airframe Considerations

Airframe configuration. - The model shown in figure 2 illustrates an airplane typical of those chosen to investigate the flight performance afforded by turbine-type engines. Since this study was limited to vehicles capable of unassisted takeoff and acceleration to their supersonic cruising speed, the design incorporates a series of compromises in order

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to achieve not only good supersonic radius in the range of flight speeds from Mach 3 to 4.5, but also satisfactory low-speed acceleration capability.

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The particular model shown in figure 2 represents a hydrogen-fueled aircraft designed to cruise at Mach 4.0 with a target altitude of 95,000 feet, while carrying a 10,000-pound payload. The actual airplane would weigh 300,000 pounds and have a fuselage length of 300 feet. Salient features are the highly swept delta wing, the canard control surface, and the six underslung engines with inlets within the pressure field of the wing.

The airframe constitutes a design considered possible by an extension of existing aerodynamic and structural practice. Alternative configurations such as those discussed in paper 4 will probably provide improved performance. However, this design will probably yield reasonable values for radius with a minimum of additional unknowns beyond those implicit in the use of hydrogen fuel.

Flight plan. - The flight plan during a typical mission is shown in figure 3, where altitude is plotted as a function of flight Mach number. The airplane takes off, accelerates, and climbs under its own power, following a path chosen to provide near-maximum radius after due regard for structural limitations on both the engine and airframe. Cruise out to the target and return are along a Breguet flight path at a constant supersonic Mach number. The airplane is required to have a 5-percent fuel reserve when landing. In the radii presented, full credit is given for distance covered during the initial climb and final descent phases of flight.

Critical regions during the flight influence the optimum combination of flight plan, engine design, and airplane design. A maximum cruise radius is sought without incurring unsatisfactory transonic acceleration or excessively long takeoff run. To achieve a good compromise among these sometimes conflicting requirements, factors such as airplane gross weight, design altitude, wing loading, and engine size have been varied. This optimization procedure was repeated, at least in part, for every engine design considered.

Airplane size and payload. - Before actual radii obtainable with such manned aircraft are discussed, there are several other factors affecting the flight analysis that should be considered. One of the more important of these is aircraft size. As a first step, calculations of airplane performance were made for several different gross weights; some of the results are shown in figure 4. Relative radius is given as a function of gross weight, where each point represents a different airplane.

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The best airplane size is largely determined by the load it is desired to carry. The airplanes represented by the upper curve are designed to deliver a payload of 3000 pounds and to have on board 5000 pounds of other fixed equipment; the lower curve is for a payload of 10,000 pounds and a fixed load of about 30,000 pounds. (Fixed load is defined to include such items as controls and electronic and hydraulic gear, etc.)

For both curves, increasing airplane weight improves the radius, mainly because most of this additional weight can be put into fuel. Also, as was noted in paper 4, the lift-drag ratio improves as airplane size increases. The point is soon reached, however, beyond which larger airplanes show no advantage. This optimum point is obviously different for the two curves shown. Equally obvious is the fact that the lighter load permits much better radii. 4793-I

Payload weight is determined by the amount of destructive power the target requires and by the accuracy with which the payload can be delivered. The fixed weight is determined largely by the ingenuity of the manufacturers of airframe and accessories as well as by tactical considerations. In order to arrive at realistic results, the examples of recent proposals for similar aircraft were accepted, and it was decided to use a payload of 10,000 pounds and a fixed weight on the order of 25,000 to 35,000 pounds. All of the following figures are based on these values.

After deciding the size payload and fixed weight that should be carried, another factor must be considered before fixing an airplane weight. This factor is the fuel used by the engine. The effects of gross weight on radius and airplane size for two fuels, hydrogen and JP, are illustrated in figure 5. For JP fuel, radius is still increasing with gross weight at an airplane weight of 500,000 pounds. For still heavier airplanes, the rate of increase rapidly diminishes. It was therefore decided to compare all the JP-fueled airplanes on the basis of the radius attainable with 500,000-pound airplanes.

For hydrogen-fueled airplanes, the radius also increases with gross weight. In this case, however, additional factors enter the picture. First, there is the problem of physical size. For the same gross weight, a hydrogen-fueled airplane is much larger than a JP airplane because of the much lower density of the hydrogen. As is shown at the top of figure 5, a 500,000-pound JP airplane is about 150 feet long, while the same weight hydrogen airplane is about 360 feet long, a ratio of more than 2 to 1. A second factor to consider is the weight of the hardware going into an airplane, which may be related to the construction cost. A JP airplane grossing 500,000 pounds has about 60 percent of its weight in fuel and thus has an empty weight of about 200,000 pounds. Because of the low fuel density, only about one-third of the weight of a hydrogen airplane is fuel, and a 200,000-pound empty weight is reached by a

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hydrogen airplane grossing about 300,000 pounds. By striking a balance among the factors of radius, airplane size, and empty weight, a gross weight of 300,000 pounds was chosen for the hydrogen-fueled airplanes to go along with the 500,000 pounds assumed for the JP airplanes. These values are used throughout the remainder of the analysis.

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Wing size. - From structural and aerodynamic considerations, a given wing type was selected for the airplanes; that is, a delta plan form of 1.5 aspect ratio, with $2\frac{1}{2}$-percent thickness ratio. The best wing size must still be determined, however. The concepts involved in sizing the wing for each application are indicated in figure 6. As a measure of wing size, wing loading is plotted along the abscissa (where low values correspond to large wings, and vice versa).

At the top of the figure, the cruise lift-drag ratio is shown for airplanes designed for various wing loadings. For the conditions considered, the maximum L/D is obtained at a wing loading of 25 pounds per square foot. Also shown are the lift-drag ratios obtained at a critical area during the climb (Mach 1.5, 36,000 ft). Highest L/D is achieved in this case at a much higher wing loading, as a result of the higher ambient dynamic pressure at this flight condition.

Wing loading also affects the weight apportionment of the airplane. Low wing loadings give large heavy wings. On the other hand, higher wing loadings increase the airplane drag, thereby affecting the required engine size. These factors in turn react on the fuel load, as shown by the middle curve. The engine is normally made larger than needed for good cruise performance in order to improve the low-speed thrust. This results in fairly low cruise afterburner temperatures.

Combining these considerations finally results in the variation of radius shown at the bottom of the figure. The optimum wing loading of 43 is materially higher than that for maximum cruising L/D. It was found necessary to repeat this optimization of both wing loading and afterburner temperature each time the design altitude or an engine parameter was changed.

Airplane Capabilities

Now that the methods used in the analysis have been described, the results for the manned airplanes are presented. The reader should be cautioned that the greater the departure from conventional configurations and the higher the flight speeds, the less precise the results become.

Target altitude. - The radius obtained by designing for various altitudes is shown in figure 7 for turbojet engines at Mach 4.0 cruise and

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1900° R turbine-inlet temperature. Radius in nautical miles is plotted against altitude over the target. Airplanes fueled with JP, JP and ethyldecaborane in the afterburner, and hydrogen have maximum radii of 1650, 2270, and 2720 nautical miles, respectively. Designing for low altitudes results in small wings with poor cruise lift-drag ratios, and also in small engines which provide marginal acceleration during takeoff or transonic flight. These factors increase the fuel consumption during both climb and cruise. Designing for high altitudes where the air is less dense requires large, heavy engines and wings. These reduce the amount of fuel that can be carried. Because of these factors, an optimum altitude exists for all fuel types - about 90,000 feet for both the JP engines and the engines using EDB in the afterburner, and 95,000 feet for the hydrogen-fueled engines. 4793-I

The hydrogen airplanes with their bulky fuselages require a proportionate increase in wing size to maintain a good lift-drag ratio. With a larger wing, it is necessary to operate at a higher altitude, which accounts for the higher optimum altitude for the hydrogen-fueled airplanes. It should be mentioned that the airplanes chosen have excellent takeoff performance and can leave the runway in distances of 3000 to 4000 feet.

Although EDB is used only in the afterburner, it appreciably improves the all-JP radius. This is true because, at high Mach numbers, the engine operates essentially as a ramjet. For example, at Mach 4 approximately 90 percent of the total heat addition occurs in the afterburner; thus, the higher heating value of the EDB substantially lowers the fuel-consumption rate.

High-energy fuels such as hydrogen and EDB are particularly advantageous for the self-boosting type of mission being considered here. Not only do they lower the cruising fuel-consumption rate but they also provide more fuel at the start of cruising, since less fuel is consumed during the climb.

By going from conventional JP fuel to hydrogen fuel with all its associated problems, the radius goes up from 1650 to 2720 miles, a 65-percent increase. This is certainly a large improvement, but the radius is disappointingly low in view of the 5500 miles often quoted as a desirable minimum radius for a long-range mission.

Assuming that the structural techniques for hydrogen-fueled airplanes can be developed without too many unanticipated difficulties, the design of such manned airplanes could be initiated immediately using the current background of engine and aerodynamic technology. This does not mean that there are no ways to improve this performance, however. The possibility of lighter payloads and fixed weights has already been mentioned. Another possibility more within the scope of this paper is that of modifying the engine or using a different type of engine.

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Air-turborocket. - Up to this point, the discussion has concerned only the turbojet engine. Similar calculations have been made for the other engine types mentioned in earlier papers. Radius as a function of target altitude for airplanes using air-turborocket engines is shown in figure 8. Data are given for three fuel combinations, again for a cruise Mach number of 4.0. Hydrogen plus liquid oxygen extends the radius somewhat over that attained with methyl acetylene and JP. The hydrogen-air liquefier engine gives the longest radius, however, at an optimum altitude about the same as for the turbojets using hydrogen fuel. The maximum radius is about 3100 miles. This is better perhaps than the turbojet, but the improvement is not outstanding. This is also about the best that can be attained with other cycles such as the fuel-rich turbofan and the hydrogen-expansion engine.

These air-turborockets have used what are considered to be practical components - things that can probably be built without a long research effort. If a little more optimism as incorporated into the analysis and it is assumed that the inlets have no additive drag during boost and that the exhaust nozzles can be designed to avoid the penalties for under- or over-expansion, performance can be improved. The maximum air-turborocket radius then rises from 3100 to about 3500 miles, as shown by the "idealized engine" symbol, a 13-percent improvement. Similar improvements can be made for the other engine types.

Design cruise Mach number. - Thus far, all the discussion has centered about Mach 4.0. The effect of cruise Mach number on radius is shown in figure 9 for two engine types, the air-liquefier air-turborocket and the turbojet using various fuels. Again, an optimistic viewpoint has been taken, in that it is assumed that the inlets have no additive drag and the exhaust-nozzle efficiency is constant. Also, the turbine-inlet temperature for the turbojets has been raised to 2500° R.

These assumptions favor the higher Mach numbers; nevertheless, designing for Mach numbers above 3.0 is detrimental to the radius. Some of the reasons for this are: (1) The engines and airframes are required to operate over a wider range of off-design conditions; (2) more energy is needed to accelerate the airplane to the peak Mach number, leaving less fuel for cruising; and (3) aerodynamic and structural efficiency deteriorates at higher speeds.

The air-turborocket affords a rather small improvement in radius over that of the turbojet. In view of these small improvements and because of the lack of practical experience with this engine, it does not seem worthwhile to develop such engines for the application being considered.

Since the air-turborocket apparently does not offer much improvement, what can be concluded about the use of turbojets? First, hydrogen seems to provide the longest radii at all the speeds considered. This is

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especially true at speeds above Mach 4.0, as it does not appear that either air-cooling or fuel-cooling with JP or EDB would be adequate for the engine. In going from Mach 3.0 to Mach 4.5 with hydrogen, however, the radius with idealized engines drops from 4000 to 2900 nautical miles. Four thousand miles is the best radius computed thus far, and even that is far from as much as is desired. Should 1100 miles be discarded so lightly, for the sake of higher flight speed? Cruising at Mach 4.0 or 4.5 probably reduces vulnerability to interception. On the other hand, cruising at Mach 3 gives longer radius; and such airplanes are undoubtedly easier to build. Thus, choosing the most desirable design speed is not easy.

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In view of current events, the radii and speeds shown in figure 9 are not especially spectacular. It should be recalled, however, that manned airplanes are being considered. They have a human crew, carry out a round-trip mission, and takeoff and land under their own power. This performance represents a very substantial improvement over the best airplanes in existence today.

What further gains can be expected? Further engine improvements can undoubtedly be made, but there is no real reason to predict any startling breakthrough. Airframe improvements do seem possible, however, and should be examined.

Advanced airframe. - The performance of the hydrogen-fueled configurations previously discussed was based on a consideration of lift-drag ratios and aircraft design techniques thought to be moderate extensions of present aerodynamic practice. The model shown in figure 10 represents a configuration incorporating some further aerodynamic improvements that can possibly be built into an aircraft. Designed for Mach 4.0 cruise at 90,000 feet, the aircraft would be 300 feet long. Important features are the flat-bottomed fuselage and the highly swept delta wing and canard control surface. Gross weight is 300,000 pounds and payload is 10,000 pounds. Hydrogen is used in four engines mounted in the rear of the fuselage with a common exhaust through one large nozzle.

A common engine inlet is located on the bottom of the fuselage near the trailing edge of the wing. The fuselage of this aircraft is somewhat larger in volume than the previous model; not only are the engines mounted in the fuselage, but the space utilization for the flat-bottomed shape is assumed to be less efficient than with the circular shape. However, no penalties due to the larger fuselage were used in the performance estimates, it being assumed that structural techniques will advance concurrently.

A comparison of the radius obtainable with the standard and the improved configurations at Mach 4, using idealized engines, is given in figure 11. The standard configuration has a radius of 3400 nautical

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miles, and the improved configuration has a radius of 4100 miles. The gain in radius is due in part to the reduction of both nacelle drag and fuselage boattail drag obtained by installing the engines in the fuselage and in part to the added lift of the flat-bottomed shape.

The improvement in radius of 700 miles with the advanced configuration results in a radius about the same as that attainable at Mach 3.0. However, this radius is still less than that desired. In addition, it should be remembered that the assumption of no structural penalties in the new configuration represents quite an advance in technology of aircraft structures.

Penalties of self-boosting. - From the analysis it has been determined that, using hydrogen as a fuel, it may be possible to design airplanes that can achieve radii from 2700 to 4100 miles at Mach 4. The lower figure is for a system representing but moderate improvements in engine and aerodynamic technique. The higher radius is for greater refinements in both of these areas. These results are for manned aircraft that takeoff and land under their own power. From time to time reference has been made to the compromises forced upon the airplanes by this mode of operation. It is of interest to look back now and see what has been sacrificed in this manner.

Consider the so-called practical engine and airframe with a maximum radius of 2720 miles. Figure 12 shows radius as a function of target altitude for Mach 4 airplanes of the standard configuration using hydrogen fuel. The lower curve is for the normal climb procedure and is reproduced from figure 7. The middle curve assumes that some other means, such as a rocket booster, has been employed to transport the airplanes with a full fuel load up to the initial cruise altitude and Mach number. For this case, the maximum radius is 25 percent higher than that obtainable with the self-boost procedure. This is but a part of the price that has been paid.

All the turbine engines for these airplanes have approached operating as ramjets at the cruise condition. Indeed, the gas-generator portion of the engine, which was required only for the climb and acceleration phase of the flight, was an undesirable appendage both in weight and engine pressure ratio at cruise. If ramjets are merely substituted for the turbine engines and the weight saved is employed to carry more fuel, the combination of the additional fuel and improved cycle performance yields the results shown by the top curve. The ramjet-powered airplane has a radius 15 percent greater than the fully boosted turbine airplane and 44 percent higher than the self-contained turbine airplane. This example is, of course, far removed from a practical man-carrying operational airplane and is used merely for emphasis.

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RAMJET MISSILES

The advantages of the ramjet as a propulsion system are more spectacular in missiles than in the realm of manned flight. Since only a one-way flight is considered, target distances are immediately doubled. For such bombardment systems all the weight associated with a crew need not be carried; and, further, advantage can be taken of the higher flight speed capability of the ramjet.

For such missiles, as was the case for manned airplanes, all the factors of engine and airframe design have been merged into the analysis of a series of missiles. The performance potential of those missiles has been determined in terms of absolute range attainable. This has been done for Mach numbers from 5 to 9 for different fuels and methods of missile boost.

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Airframe and Engines

Configuration. - The general aerodynamic configuration of the missiles analyzed is illustrated by the models in figures 13 and 14. This particular model represents a hydrogen-fueled Mach 7.0 missile having a gross weight of 38,400 pounds, including a 10,000-pound payload and a fixed weight of 1550 pounds. For the reasons discussed in paper 3, a single ramjet engine installed in the fuselage is used. A simple two-shock inlet is employed because of the research and development problems yet to be solved with the higher performance inlets. The exhaust nozzles have fixed areas, with a slightly conservative velocity coefficient of 0.96 assumed. The engines are of double-walled construction, and fuel was used as the coolant except when diborane was used for fuel, in which case water was supplied for cooling. The missile is a canard configuration with a fuselage fineness ratio of 20 and a wing sweep of 72.5°. The LOX-JP boosters (attached as shown in fig. 14) bring the total weight up to 150,000 pounds at ground launch.

Flight path. - The rocket booster carries the missile to the initial cruise altitude and cruise Mach number. After booster separation, the missile follows a Breguet flight path to the target, climbing perhaps 5000 feet. Near the target, using normal procedure, the engine is cut, a pull-up is executed to reduce velocity, and dive-in occurs.

Fuel type. - As the first step of the analysis, the suitability of various fuels was examined. This study gave the results shown in figure 15, where relative range is plotted as a function of missile plus booster weight for operation at Mach 5. The payload is 10,000 pounds, and chemical-equilibrium expansion in the exhaust nozzle is assumed. Data are given for three fuels: liquid methane, liquid diborane, and hydrogen. Liquid methane was selected as the most promising hydrocarbon fuel because of its high heat-sink capacity - more than twice that of JP.

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For all fuels, the range increases with missile-plus-booster weight for the same reasons that the larger airplanes were beneficial. Comparison of the fuel types shows clearly that methane, with its low heating value, is inferior to hydrogen. Except for one fault, liquid diborane (the dashed curve) is as good as hydrogen. The difficulty is that diborane is a very poor heat sink and cannot be used to cool the engine. If enough water to cool the engine is carried, the range is cut in half, despite the assumption that the vaporized water provides some additional thrust with an impulse of 150 seconds.

This concern about liquid-cooling results from the fact that at Mach 5 the high stagnation temperature of air precludes the use of conventional cooling liners. One way the cooling problem might be alleviated would be to use insulation in the combustion chamber (e.g., foamed ceramics). Then the diborane would not be so heavily penalized for the cooling water. However, at Mach 5, hydrogen still seems clearly superior to the other fuels with respect to range. The superiority is even more pronounced at higher Mach numbers where aerodynamic heating becomes more severe.

It should be noted that at this Mach number (i.e., 5), liquid methane can yield 75 to 80 percent of the range attainable with hydrogen. As will be established in a following section, this represents an appreciable capability. If Mach 5 is considered an acceptable flight speed, liquid methane should be seriously considered as an alterante fuel, although results are presented primarily for hydrogen-fueled missiles.

Structural weight. - Before discussing actual performance numbers, one more important facet of this picture needs to be defined. This is structural weight. The extreme sensitivity of range to missile structural weight is illustrated in figure 16. Here relative range is plotted against ratio of structural to missile weight for cruise Mach numbers of 7.0 and 9.0 and a total missile weight of 30,000 pounds. For example, at Mach 7.0 a change from 0.3 to 0.4 in ratio of structural to missile weight reduces the relative range from 1 to 0.6, a 40-percent loss.

The schedule of structural weight used in the analysis is given in figure 17. Here the ratio of structural to missile gross weight is plotted against missile gross weight for cruise Mach numbers of 5, 7, 8, and 9. The payload is 10,000 pounds and the fuel is hydrogen. To keep structural weights realistic, the equations were based on weights of current design proposals in the industry, including boost-glide vehicles. At Mach 5.0 stainless-steel construction was assumed. At Mach 7.0, with its higher metal operating temperatures, the material was changed to a super alloy, which has a higher density. The increase in metal density and the higher operating temperatures account for the weight increase between Mach 5.0 and 7.0. Weight increases above Mach 7.0 were made to allow for leading-edge cooling and operation of the metal structure at still higher temperatures.

Missile Capabilities

Target altitude and Mach number. - Figure 18 shows range as a function of target altitude for missiles with cruise flight Mach numbers from 5.0 to 9.0. The missiles have a takeoff weight of 150,000 pounds with a payload of 10,000 pounds; LOX-JP rockets provide full boost to the initial cruise point. At each flight Mach number there is an optimum altitude, an optimum determined by the same factors discussed for the turbojet airplanes. The optimum altitude increases from 105,000 feet at Mach 5.0 to 110,000 feet at Mach 7.0. At Mach 8.0 and 9.0, however, it increases only slightly owing to the increase in structural weight. To reduce the contribution of aerodynamic heating to the total heat load, it has been elected at Mach 8 and 9 to operate at altitudes somewhat higher than that for maximum range, as shown by the tick marks. Accordingly, the portions of the curves where heating is considered excessive are shown by broken lines. Data given in succeeding figures correspond to the tick marks. Even at the higher altitude, it may well be necessary to provide internal insulation in regions of high heat flux in the engine to permit operation at Mach 9.

Despite the large 10,000-pound payload and relatively modest 150,000-pound missile-plus-booster weight, range is not a major problem. At Mach 5.0 the range is 10,500 nautical miles. At Mach 7.0 the range is 9000 miles. The ranges at Mach 8.0 and 9.0 are still respectable; however, it must be recognized that at these speeds the data are less certain because of more uncertainty in structural weight and the more serious consequences if chemical-equilibrium expansion in the nozzle is not fully achieved.

Gross weight. - The ranges at Mach 5 and 7 appear to be more than adequate. Suppose, then, that the problem is approached from a different viewpoint; that is, how little weight can be used and still deliver the specified payload for the ranges of interest. There is considerable interest at present in ranges between 6500 and 8500 nautical miles.

In figures 19 and 20, missile-plus-booster weight is shown as a function of payload for Mach numbers of 5 to 9 for these ranges. As is to be expected, an increase in payload requires a larger carrier and hence an increase in missile-plus-booster weight. Most of the discussion to this point has centered around a 10,000-pound payload. It has been suggested that an air-breathing missile may be able to use mid-course correction, say by map comparison, and thus reduce circular probable errors over the target. Suppose for this reason, or because bomb yields are improved, the payload weight can be reduced to 3000 pounds, for example. With this payload, the 6500-mile target may be hit at Mach 7 with a total takeoff weight of only 61,000 pounds. The range of 8500 miles would require a total weight of 81,000 pounds.

At the other extreme, suppose a bigger payload were needed. A 20,000-pound payload, perhaps a cluster of smaller bombs, could be delivered a distance of 6500 miles at Mach 7 for a weight at takeoff of 200,000 pounds. The corresponding value for an 8500-mile range is 239,000 pounds, which is about the same as current intercontinental ballistic missiles.

Comparison with ICBM. - To provide a familiar plane of reference, this weight and payload comparison with current ICBM's should be amplified. It should be emphasized that such ballisitic missiles reflect present technology, whereas the ramjet missile incorporates advanced concepts. It should also be emphasized that this is not an attempt to compare overall merit, since it is beyond the scope of this paper to assess factors such as relative cost, vulnerability, or target accuracy.

For equal takeoff weight, the Mach 7.0 ramjet missile will deliver seven times the payload of the current ICBM, and deliver it 1000 nautical miles farther. Or, looking at it another way, the same payload can be delivered 1000 miles farther for 27 percent of the current ICBM takeoff weight. This weight comparison may not be as unfair as it would appear at first glance, because the rocket booster for the Mach 7 ramjet missiles being considered is 75 percent of the total weight. These boosters employ the same technology as used in current ICBM's. High-energy rocket propellants should provide reductions in the takeoff weights for both systems.

Ramjets for boost. - Thus far the discussion has been confined to full rocket boost to the cruise Mach number. It is well known, however, that ramjet impulses are much higher than rocket impulses in the supersonic Mach number range of interest here. Accordingly, the use of a ramjet boost stage from Mach 3.0 to 7.0 was examined. A missile configuration incorporating a ramjet boost stage is shown in figure 21. The missile weighs 27,400 pounds, and the boost stage 7800 pounds. The ramjet booster contains a separate engine and hydrogen fuel tank. The design Mach number of the fixed-geometry engine is 4.5, using a simple 4° ramp inlet. For compatibility with the booster stage, the missile was altered to a high-wing design with twin inlets for the cruise engine. Double-shock inlets were used for the cruise engine, which is inoperative during boost.

The boost trajectory with this system is shown in figure 22 as a plot of altitude against Mach number. Conventional rocket boost is employed to Mach 3.0 at 47,000 feet, where separation occurs. Acceleration with the booster ramjet then occurs to Mach 7.0 at a constant dynamic pressure of 1800 pounds per square foot. This is followed by a constant Mach number climb on the booster engine to the initial cruise altitude of 100,000 feet. The ramjet boost stage then separates and cruise begins.

The effect of this ramjet boost stage on weight is illustrated in figure 23. Gross weight of the Mach 7.0 cruise missile is 35,200 pounds.

Range is constant at 6100 nautical miles with a 10,000-pound payload. Studies have shown that for some applications, such as boost-glide vehicles, the total takeoff weight is strongly affected by the size of the engine in the ramjet boost stage. Accordingly, total missile-plus-booster weight is shown as a function of the size of the ramjet booster engine, where the engine size is specified in terms of net thrust at Mach 3.0. At the left, for comparison, is shown a weight breakdown for full rocket boost. The total weight is subdivided into rocket fuel, total ramjet fuel, and total weight of hardware, which includes structure, tanks, engines, payload, and fixed weight.

Miminum total weight of 102,000 pounds is achieved at an engine size that corresponds to 32,000 pounds of thrust at Mach 3.0; and the weight is relatively constant in the thrust range covered for this application. This represents a one-third reduction in total weight from the 149,000 pounds for full boost on conventional rockets. From the weight breakdown it is seen that the hardware weight is virtually unaffected, and that the saving is entirely in rocket fuel. It may be concluded, then, that the use of a ramjet boost stage would reduce markedly the missile-plus-booster weights presented in figures 19 and 20. There is certainly a question, however, as to whether the saving in rocket fuel would warrant the added complexity of the ramjet booster stage.

Air-to-surface mission. - Within the scope of this discussion there lies the interesting possibility for launching a ramjet missile from a turbine-powered manned aircraft. At takeoff and up to Mach 3.0, the ramjet missile with its ramjet boost stage could ride "piggy-back" on a hydrogen-fueled turbine-powered aircraft. At Mach 3.0 and the maximum radius of the manned aircraft, the missile would leave the mother plane and accelerate to Mach 7.0. At this point it would drop its boost stage and continue to the target at Mach 7.0 cruise. The case analyzed would have a takeoff weight of 300,000 pounds, with the missile weight replacing fuel and payload of the mother airplane. In the following range calculations, it was optimistically assumed that the lift-drag ratio of the combination was the same as that of the mother airplane. This is perhaps compensated for to some extent, however, by the fact that no effort was made to reoptimize the bomber for this particular mission.

The capabilities of this combination of manned aircraft and ramjet missile are indicated in figure 24, where total range is plotted against ramjet-missile plus ramjet-booster weight for payloads of 1500 and 10,000 pounds. Hydrogen fuel was used for both aircraft and missile. Over-all missile length, including the ramjet booster, is cross-plotted. For example, a 155-foot missile weighing 35,000 pounds and carrying a 10,000-pound payload has a total range of 9300 miles. Of this range, 3025 miles are attributed to the distance traveled by the mother aircraft before launching the missile. If a range of only 8500 nautical miles is required, and lighter payloads are acceptable, then the extra range capabilities of a given gross weight might be traded for higher delivery Mach numbers. Considerable flexibility is provided by this combined system, since the mother aircraft could still be used as a bomber.

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One of the major problems when carrying a hydrogen-fueled missile is evaporation of the missile fuel during the flight time on the mother aircraft. If evaporation had been considered in the preceding example, it is estimated that the total target distance would have been reduced from 9300 to 8300 nautical miles, a 10-percent loss. This loss may be reduced by schemes of varying complexity and additional weight.

If delivery of the missile at Mach 5 is acceptable, the use of methane as a missile fuel appears attractive. The somewhat higher temperature of liquid methane would alleviate the fuel-evaporation problem to some extent and still give ranges approaching 7700 nautical miles for a 35,000-pound missile carrying a 10,000-pound payload.

CONCLUDING REMARKS

This paper has presented the estimated capabilities of missiles and manned aircraft designed for long-range bombardment missions and powered by chemically fueled, air-breathing engines. To help put these results in the proper perspective, figure 25 shows a plot of unrefueled radius as a function of flight Mach number for manned turbine-powered bomber airplanes. The curves on this figure indicate the broadening of the horizons for such aircraft over the last few years. The circled points indicate the unrefueled capabilities of current operational and prototype bomber aircraft. All but one of these airplanes have only subsonic capability and have radii from 2000 to 3500 miles. The one airplane with supersonic capability was designed for a split mission and for this reason as well as its small size has relatively poor supersonic radius capability.

In 1955 it was considered logical to perform mission studies for turbine-powered airplanes up to cruise Mach numbers of 3.0. With hydrocarbon fuels, radii of the order of 1200 miles at Mach 2 and 700 miles at Mach 3 were considered possible. At that time hydrogen entered the picture as a possible turbine-engine fuel and, with this fuel, the radius attainable rose to 2000 miles at Mach 2 and about 1300 at Mach 3.

In the meantime large advances in aerodynamics were achieved. Combining airplanes incorporating these advances with fairly conventional turbojet engines using hydrocarbon fuels may make possible radii of the order of 3000 miles at Mach 3. Such aircraft are typified by the WS-110 proposals indicated by the square symbol in the figure. If hydrogen fuel and turbine engines of varying degrees of improvement are used with such airplanes, radii lying within the shaded area are possible. At Mach 4, for example, a 3400-mile radius is predicted. If still more advanced airplane configurations are employed, the latter figure can be increased to 4100 miles. This last value should not be construed as an ultimate limit, because other possible improvements, such as long runs of laminar boundary layer on the airplane, have not been included in the analysis. These radii are all for payloads of 10,000 pounds and fixed loads of the order of 30,000 pounds. If lighter weapons or lighter accessory weights can be considered, these radii can, of course, be increased still further.

To sum up the picture for turbine-powered manned airplanes, it is felt that, through the use of hydrogen fuel and improved engines and airplanes, it is possible to achieve unrefueled radii at Mach 4 at least equivalent to those currently attainable at subsonic speeds. This increase in flight speed is often considered as desirable from the standpoint of vulnerability; but, as noted before, the unrefueled radius falls short of the minimum for intercontinental missions.

When the hydrogen-fueled ramjet missile is included, the picture broadens to that given in figure 26, where unrefueled target distance is given as a function of cruise Mach number. The ramjet-missile curve represents fully rocket-boosted configurations as well as those employing partial ramjet boost. All these missiles are capable of delivering 10,000-pound payloads. The target distances for these missiles easily exceed the most stringent requirements, and targets can be reached at speeds up to Mach 9.

If the partial-ramjet-boost missile of Mach 7 cruise design is combined with a Mach 3 hydrogen-fueled airplane as a carrier, target distances ranging from 10,000 miles for the 10,000-pound payload to 14,000 miles for a 3000-pound payload may be attained, as shown by the shaded bar. Such a system has an inherent flexibility, as each component can be used separately for different applications.

This, then, is the picture that can be painted for missiles and manned airplanes for long-range applications powered by air-breathing, chemically fueled engines.

This discussion has not attempted to evaluate such factors as cost, development effort, development time, or vulnerability. Factors such as these must certainly be considered in deciding whether to develop a new weapons system, whether it be a manned bomber, a ramjet missile, or some other system such as an ICBM. It is hoped, however, that the information presented herein will provide a useful foundation on which such decisions can be logically based.

TURBINE POWERPLANTS SELECTED

ENGINE	TURBOJET	TURBOJET	TURBOJET	AIR TURBOROCKET (AIR LIQUEFACTION)
DESIGN FLIGHT, M_0	3.0	4.0	4.5	4.0
SEA LEVEL COMPRESSOR P. R.	5.0	2.3	2.3	1.71
TURBINE INLET TEMP, °R	2500	1900 2500	2500	2000
BOOST AFTERBURNER TEMP, °R	4000	4000	4000	4000

CS-14657

Table I

STANDARD HYDROGEN FUELED CONFIGURATION

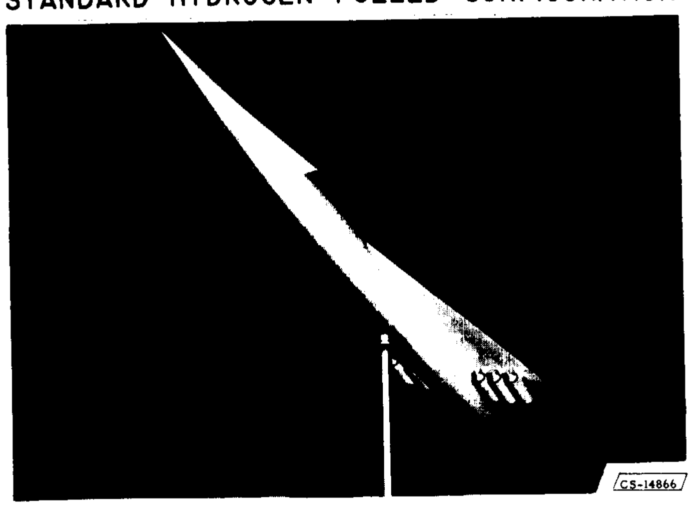

Figure 2

ZONES OF ENGINE APPLICATION CONSIDERED

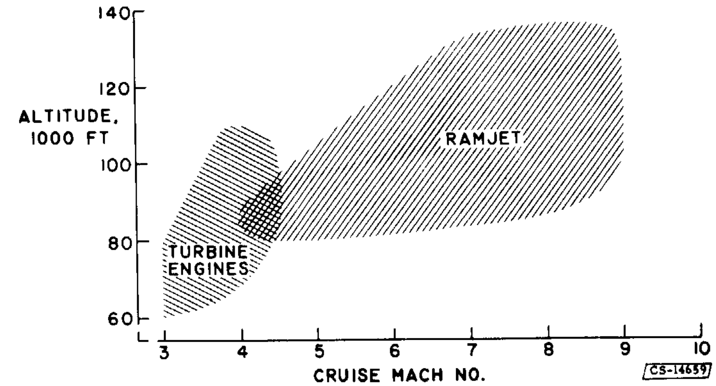

Figure 1

TYPICAL CLIMB PATH

CRUISE MACH NO., 4

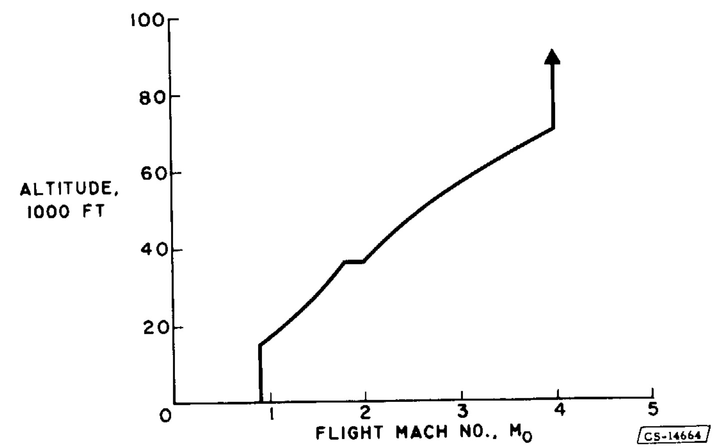

Figure 3

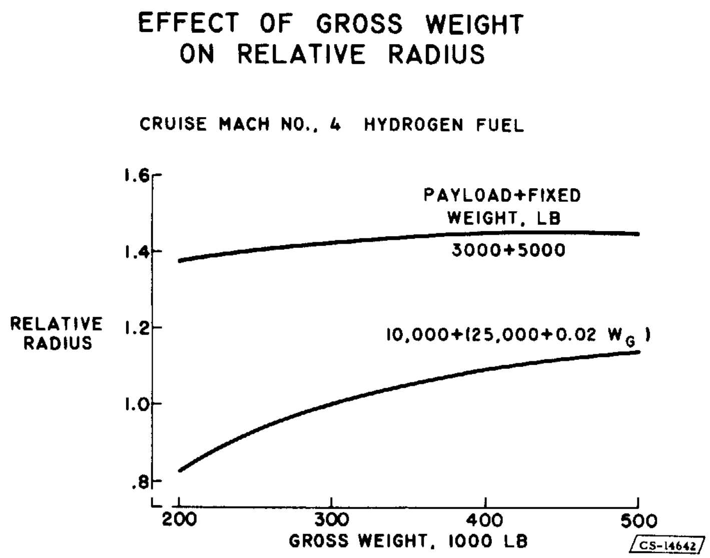

Figure 4

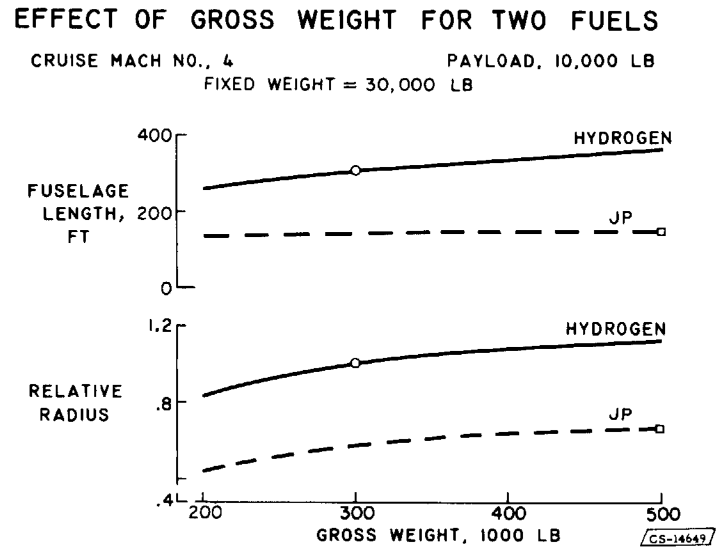

Figure 5

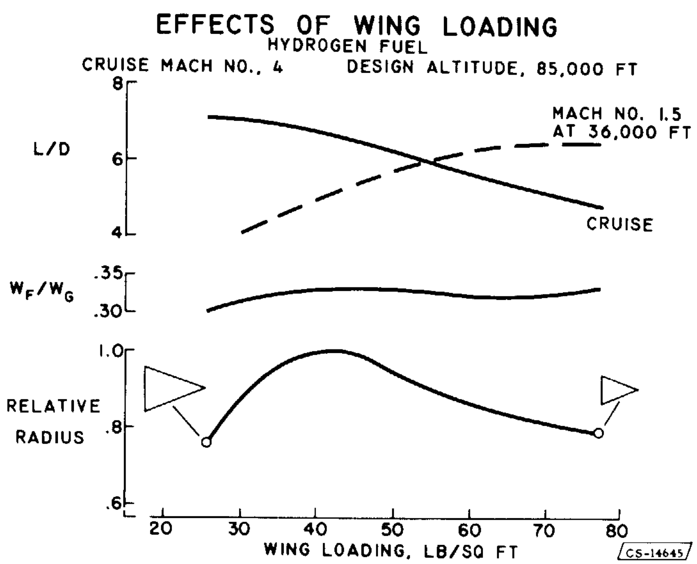

Figure 6

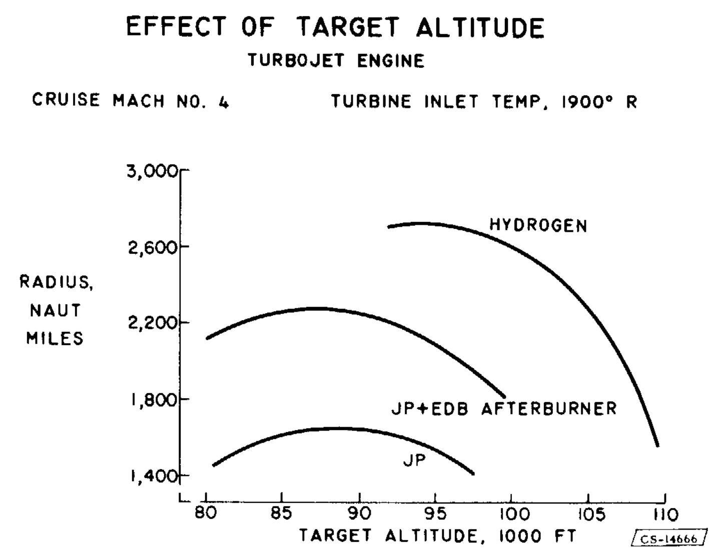

Figure 7

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RADIUS WITH AIR-TURBOROCKET ENGINES

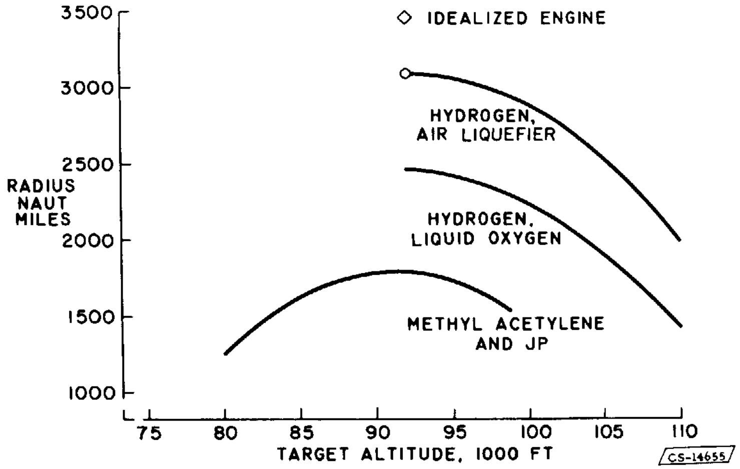

Figure 8

EFFECT OF CRUISE MACH NUMBER

IDEALIZED ENGINES

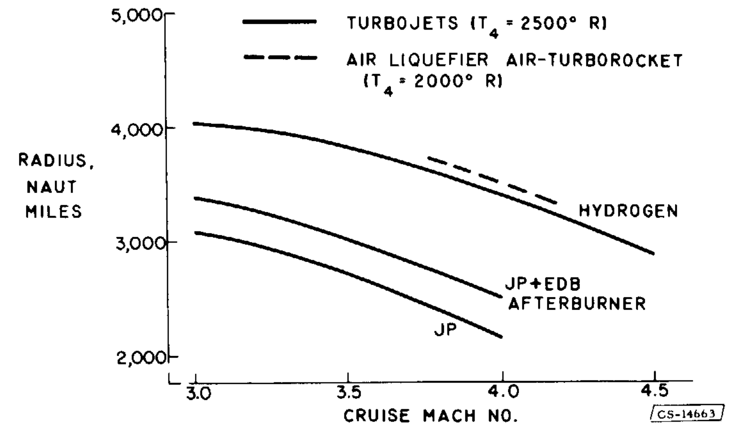

Figure 9

IMPROVED HYDROGEN FUELED CONFIGURATION

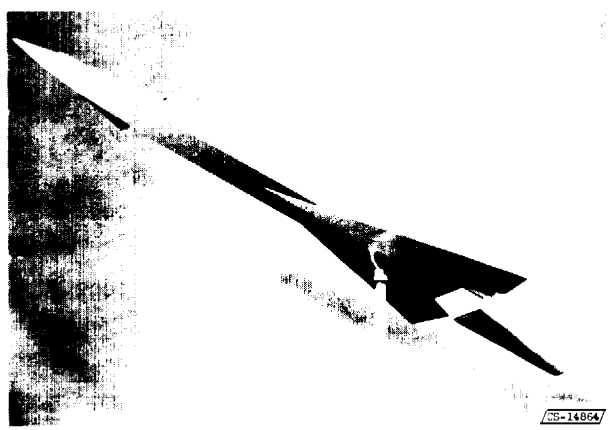

Figure 10

EFFECT OF AIRFRAME IMPROVEMENTS

CRUISE MACH NO., 4 HYDROGEN FUEL IDEALIZED ENGINES

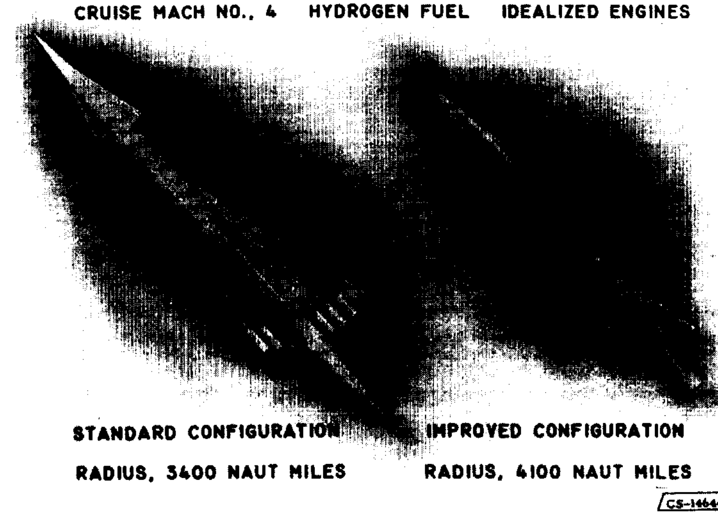

Figure 11

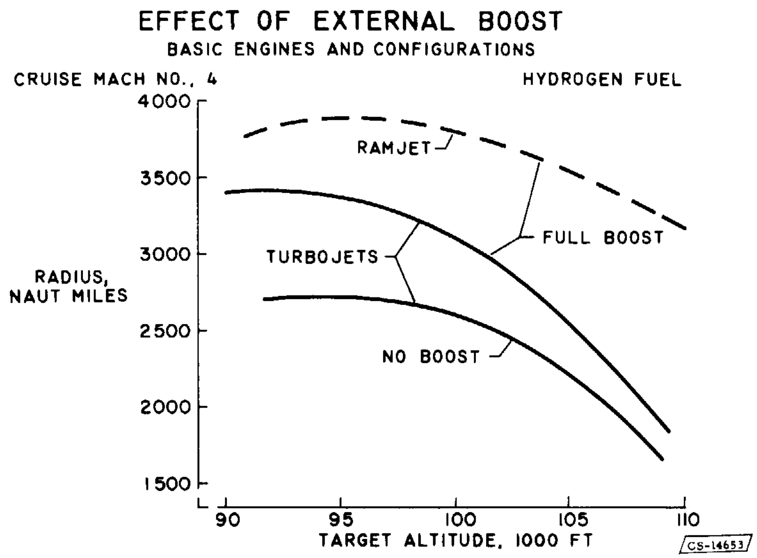

Figure 12

RAMJET MISSILE

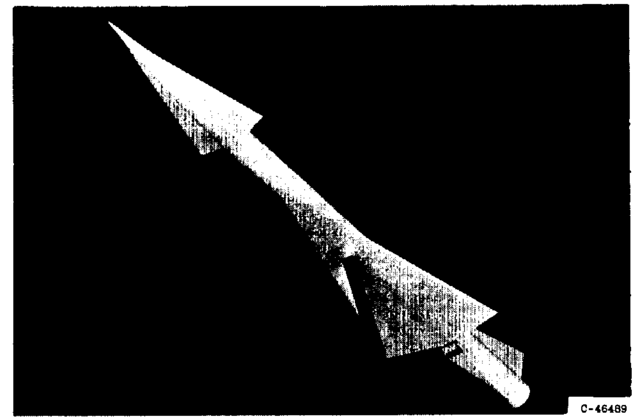

Figure 13

RAMJET MISSILE + ROCKET BOOSTER

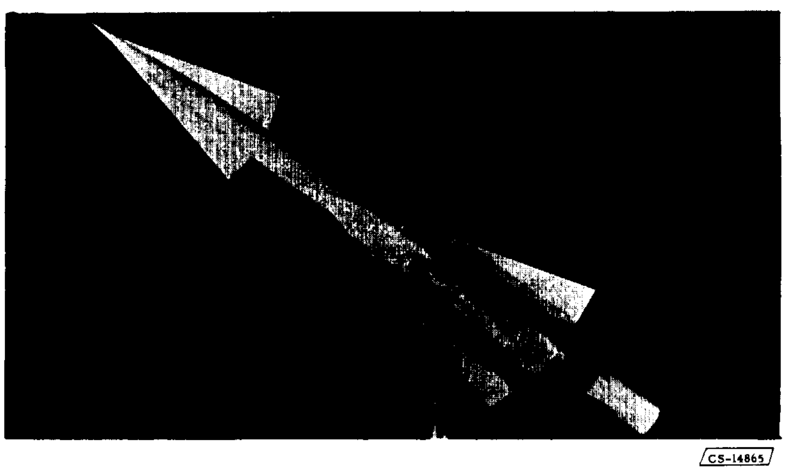

Figure 14

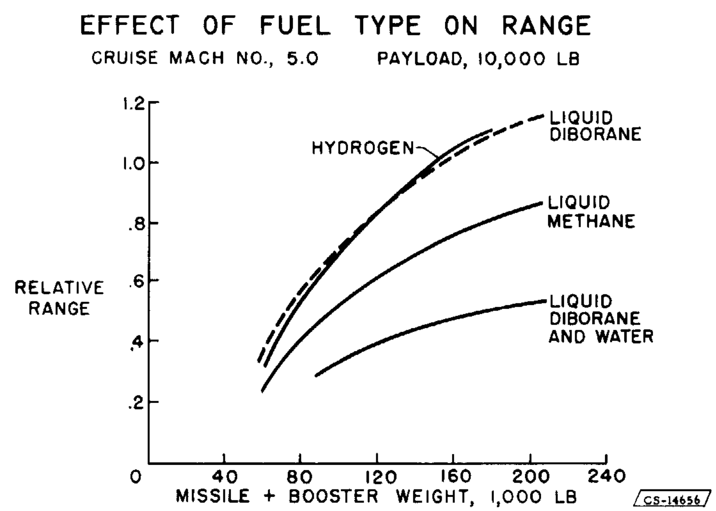

Figure 15

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EFFECT OF STRUCTURAL WEIGHT ON RANGE

MISSILE WEIGHT, 30,000 LB   PAYLOAD, 10,000 LB

HYDROGEN FUEL

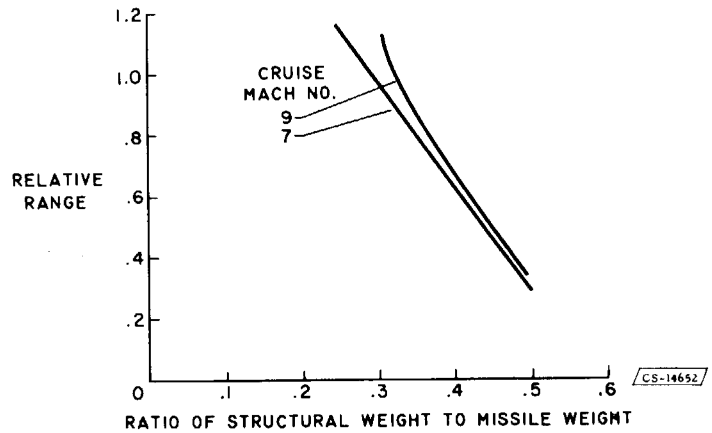

Figure 16

STRUCTURAL WEIGHT SCHEDULE

HYDROGEN FUEL   PAYLOAD, 10,000 LB

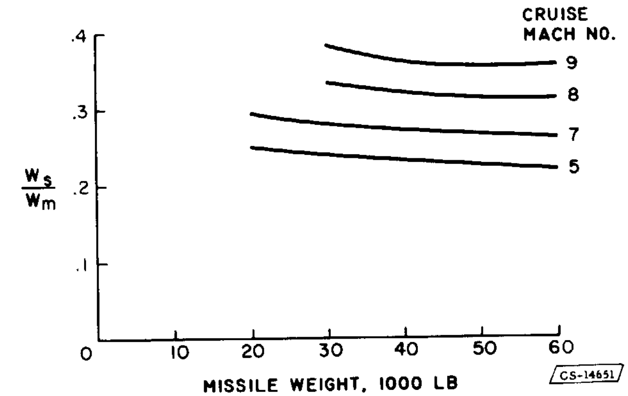

Figure 17

EFFECT OF ALTITUDE AND MACH NUMBER ON RANGE

HYDROGEN FUEL   PAYLOAD, 10,000 LB W_{M+B}, 150,000 LB

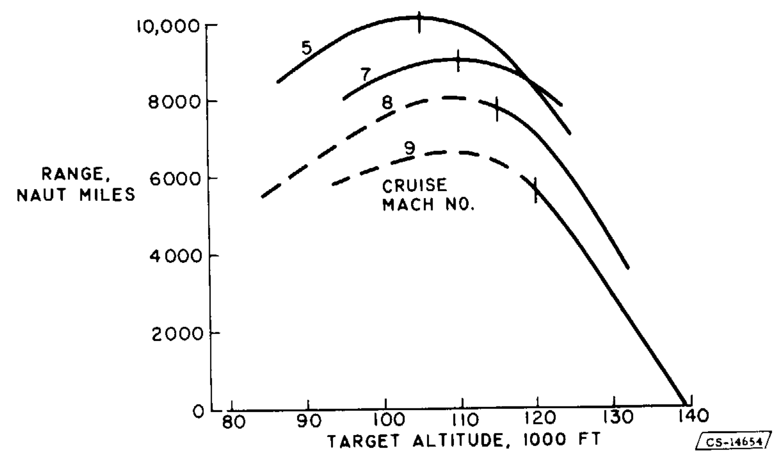

Figure 18

WEIGHT REQUIRED FOR 6500 NAUTICAL MILE RANGE

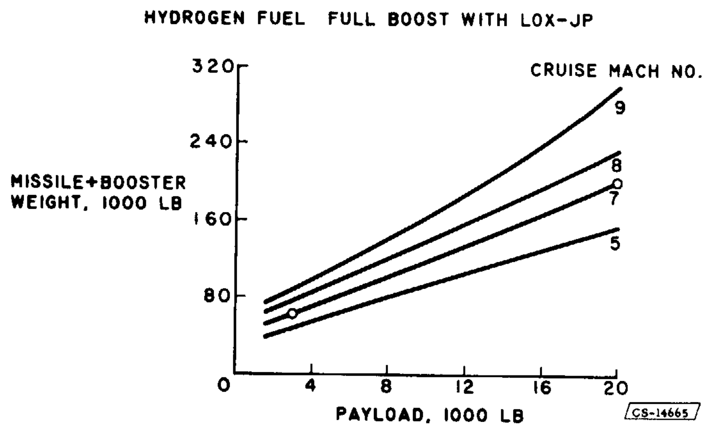

Figure 19

WEIGHT REQUIRED FOR 8500 NAUTICAL MILE RANGE

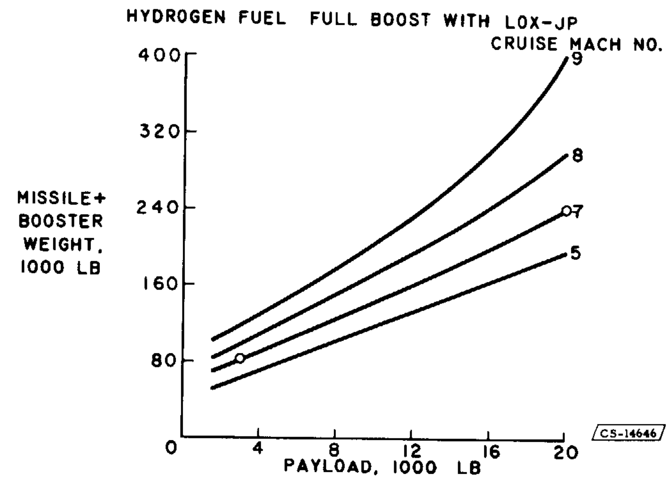

Figure 20

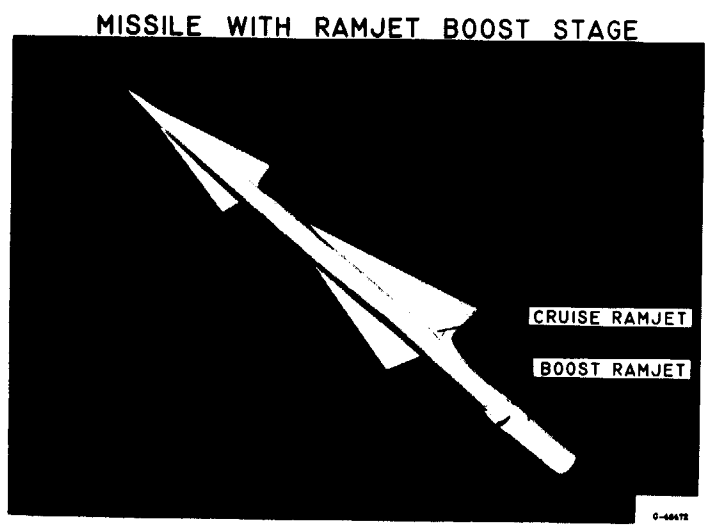

Figure 21

TYPICAL FLIGHT PATH WITH RAMJET BOOST STAGE

CRUISE MACH NO., 7

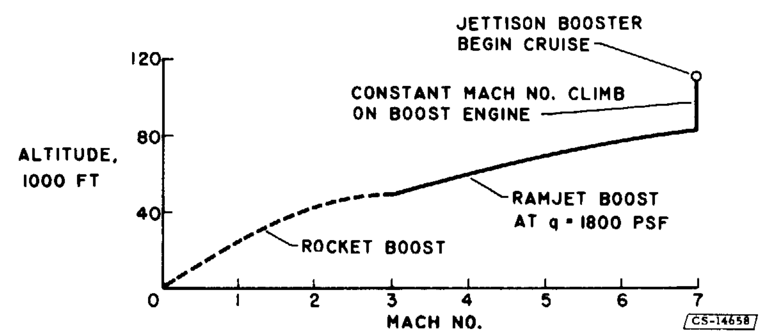

Figure 22

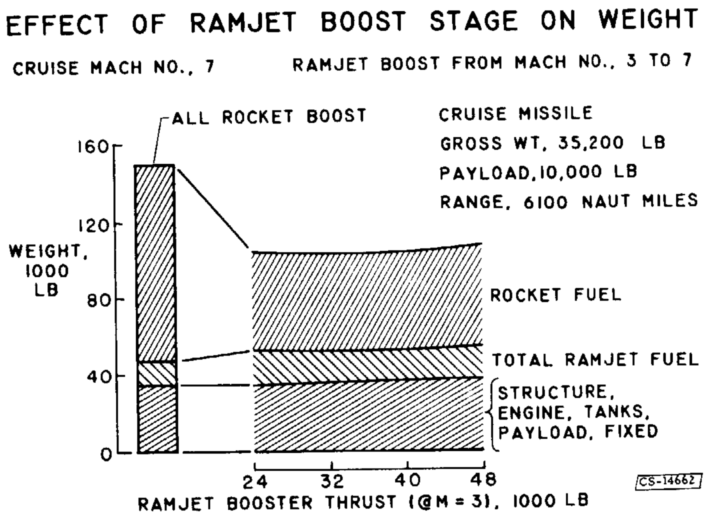

Figure 23

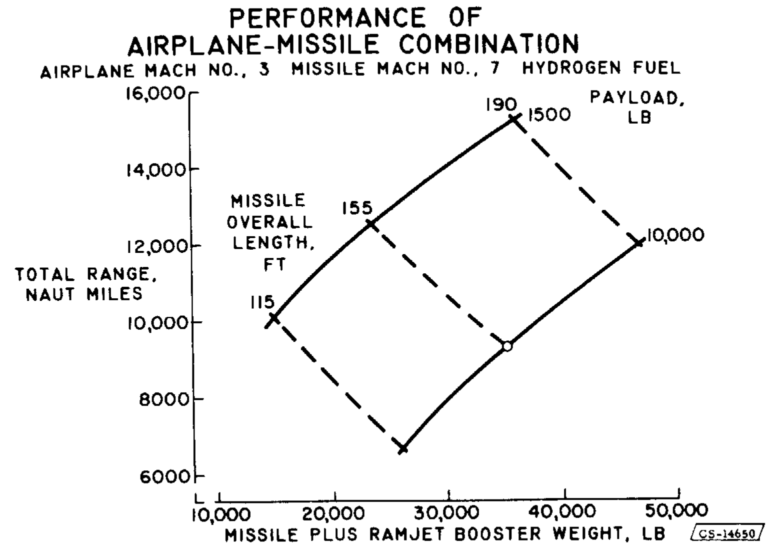

Figure 24

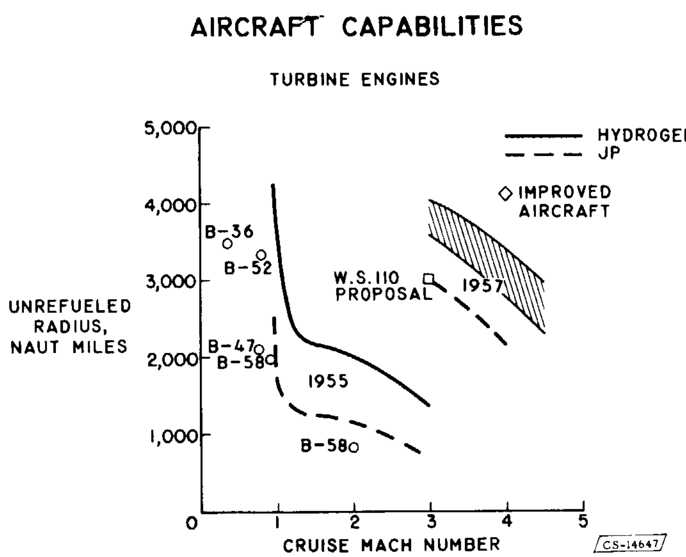

Figure 25

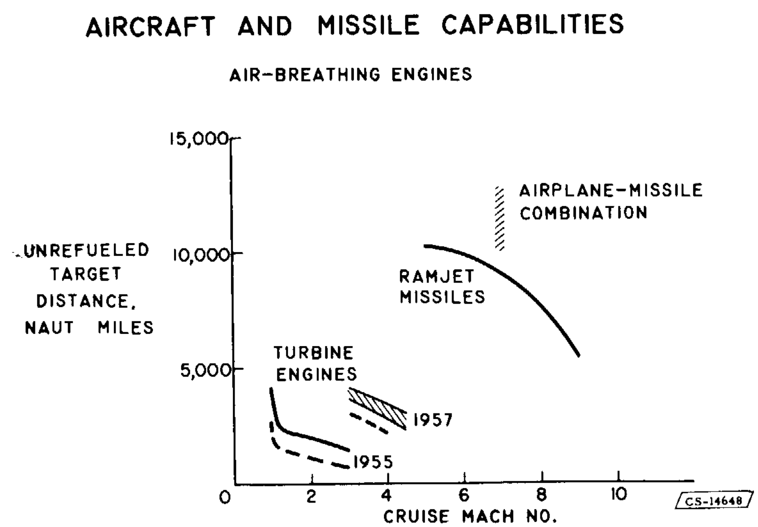

Figure 26

[redacted]

[redacted]